

*The Neutral ISM in Starburst Galaxies*  
*ASP Conference Series, Vol. 320, 2004*  
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## Molecular Gas Chemistry in Starbursts and AGN

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**Abstract.** We present the main results of an extragalactic survey aiming to study the chemistry of molecular gas in a limited sample of starburst galaxies (SB) and AGN hosts. Observations have been carried out with the IRAM 30m telescope and the Plateau de Bure Interferometer (PdBI). The high resolution/sensitivity of the PdBI has made possible to obtain high quality images of the galaxies using specific molecular gas tracers of Shock Chemistry, Photon Dominated Regions (PDR) and X-ray Dominated Regions (XDR). The occurrence of large-scale shocks and the propagation of PDR in starbursts can be studied. We also discuss the onset of XDR chemistry in AGN.

### 1. Evolution of Molecular Gas Chemistry in SB and AGN

Multi-wavelength based evidence indicates that the properties of molecular gas in SB and AGN hosts differ from that of quiescent star forming disks. The spectacular energies injected in the gas reservoirs of SB and AGN coming as strong radiation fields (UV, X-rays,...), powerful winds and jets can create a particularly harsh environment for ISM. A complete understanding of the physical/chemical evolution of molecular gas in 'active' galaxies requires the use of specific tracers of the relevant energetic phenomena that are at work all the way along the starburst sequence: large-scale shocks, strong UV-fields and nuclear X-ray irradiation. We have used the high-resolution/sensitivity of the IRAM 30m telescope and the PdBI to study a limited sample of prototypical SB and AGN.

#### 1.1. Unveiling Shock Chemistry in SB

We have carried out a 30m multi-transition survey searching for the thermal emission of silicon monoxide (SiO) in a dozen prototypical SB galaxies including NGC 253, M 82 and NGC 1068. Studies of galactic clouds point out to SiO as a privileged tracer of shocks in the molecular gas phase. Shocks can significantly increase SiO fractional abundances to  $X(\text{SiO}) \sim 10^{-8}$ . Our survey shows that SiO emission is widespread in the circumnuclear disks (CND) of SB on scales ranging from 100 pc to 700 pc. The estimated SiO abundances vary within the sample from  $X(\text{SiO}) \sim 10^{-9}$  in NGC 253 to 1/50 of this value in M 82. Physical

parameters of SiO clouds are also very different, suggesting different scenarios for shock chemistry.

The first PdBI SiO maps obtained in NGC 253 and M 82 have given invaluable insight into the different mechanisms driving large-scale shocks in the molecular gas disks of SB (García-Burillo et al. 2000; 2001). While SiO emission is detected mainly in a 700 pc-diameter CND in NGC 253 (García-Burillo et al. 2000), the emission of SiO extends noticeably out of the galaxy plane in M 82, tracing the disk-halo interface where episodes of mass injection from the disk are building up the gaseous halo (García-Burillo et al. 2001; see Fig. 1). Large-scale shocks are driven by massive star formation and bar density waves inside the disk of NGC 253. In M 82, however, shocked molecular gas appears forming a 500 pc chimney and a giant supershell. The strikingly different distributions and average fractional abundances of SiO in NGC 253 and M 82 are suggestive of an evolutionary link between these SB; the latter pictures the M 82 starburst as a more evolved episode.

More recently, the detection of SO<sub>2</sub>, NS and NO emission in NGC 253 have confirmed that shock chemistry is at work in the nucleus of NGC 253 (Martin et al 2003, submitted).

### 1.2. Propagation of PDR Chemistry in SB

We have mapped the emission of the formyl radical (HCO) in the nucleus of M 82 (García-Burillo et al. 2002). HCO is known to be enhanced in the interfaces between the ionized and molecular gas, making it a privileged tracer of PDR. The 5" HCO map of M 82, the first obtained in an external galaxy, shows a ring-like distribution, also displayed by other molecular/ionized gas tracers in this galaxy. Most remarkably, the rings traced by HCO, CO and HII regions are nested, with the HCO ring lying in the outer edge of the molecular torus (see Fig. 2). The high overall abundance of HCO in M 82 ( $\sim 4 \times 10^{-10}$ ) indicates that its nuclear disk has become a giant PDR of  $\sim 650$  pc size. Furthermore, the existence of a nested ring pattern with the highest HCO abundance being estimated in the outer ring ( $\sim 0.8 \times 10^{-9}$ ), suggests that PDR chemistry is propagating in the disk.

The PdBI maps of M 82 made in SiO and HCO illustrate how two different gas chemistry scenarios can be simultaneously at play in the same galaxy. The strong UV fields of the M 82 starburst have created a giant PDR inside the disk, while the expansion of hot gas created by successive SN explosions entrains neutral gas into the halo driving shocks located in the disk-halo interface of the galaxy.

### 1.3. XDR Chemistry in AGN: the nucleus of NGC 1068

Molecular gas in the CND of AGN hosts can be exposed to strong X-ray irradiation. Contrary to UV photons, X-rays can penetrate gas column densities out to  $N(\text{H}_2) \sim 10^{23-24} \text{ cm}^{-2}$  before being attenuated. Therefore, XDR could be the dominant sources of emission for the molecular gas in the vicinity of AGN (Maloney et al. 1996). Tantalizing evidence that the chemistry of molecular gas in the CND of AGN is 'exotic' came from the large HCN/CO abundance ratio measured in the nucleus of the Seyfert 2 galaxy NGC 1068 (Tacconi et al. 1994), first interpreted as a signature of enhanced oxygen depletion in the NLR.

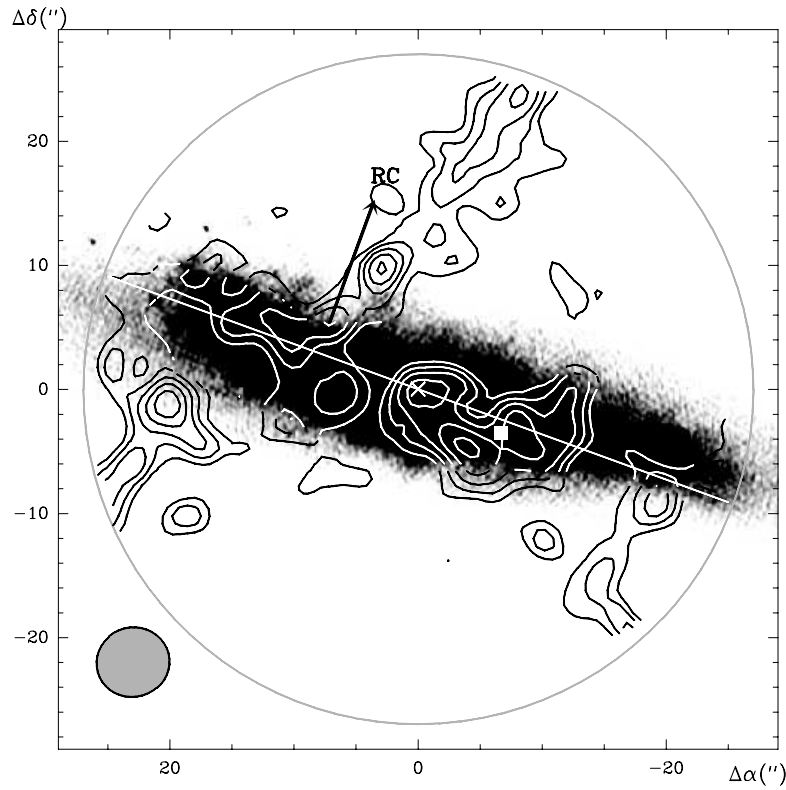


Figure 1. Integrated intensity map of SiO( $v=0, J=2-1$ ) emission (contours) in the central 700 pc of M82 obtained with the IRAM PdBI from García-Burillo et al. (2001). The SiO map is overlaid with the 4.8 GHz radio continuum image (grey scale) of Wills et al. (1999). Two major features unveil large-scale shocks in the disk-halo interface of M82: a 500 pc chimney (coincident with a radio continuum chimney: RC) and a supershell enclosing SNR 41.95+57.5 (squared marker).

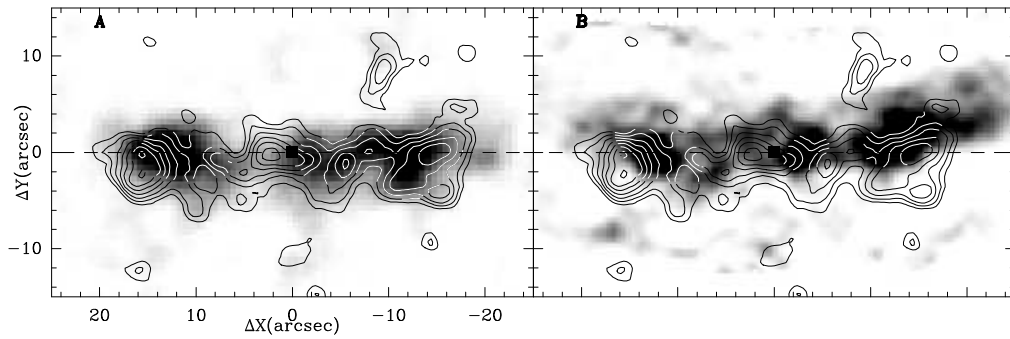


Figure 2. Propagation of PDR chemistry in the M82 nuclear starburst is probed by the detection of widespread HCO ( $F=2-1$ ) emission (from García-Burillo et al. 2002). The nested ring morphology of the 650 pc HCO disk (in contours) is compared with the H<sup>13</sup>CO (A) and CO (B) disk emissions (both in grey scale). The strong variations of the line intensity ratios indicate the propagation of PDR chemistry in M82.

In the course of our ongoing 30m survey, we detected SiO emission in the starburst ring of NGC 1068. Most remarkably, we detected also SiO emission coming from the CND torus of NGC 1068, i.e., from a source mostly unrelated to recent star formation. We derived an SiO abundance enhanced out to  $\sim 10^{-9}$  in the CND. Silicon chemistry in the CND of NGC 1068 is driven either by X-rays or by violent shocks near the central engine. To bring some light into the 'obscuring torus chemistry' we made complementary observations with the 30m telescope and PdBI for eight molecular species, purposely chosen to fully explore the predictions of XDR models for the molecular gas phase. Observations included several lines of CN, HCO,  $\text{H}^{13}\text{CO}^+$ ,  $\text{H}^{12}\text{CO}^+$ ,  $\text{HOC}^+$ , HCN, CS and CO. A first analysis of this survey, presented by Usero et al. (2003), has shown that the bulk of the molecular gas emission in the CND of NGC 1068 can be interpreted as coming from a giant XDR.

## 2. Conclusions

The advent of highly sensitive interferometers has made possible to study the complex molecular inventory of galaxies, going beyond the classical 'CO maps'. In particular, the information provided by molecular gas tracers of peculiar chemistry scenarios such as PDR, XDR, and Shock Chemistry is a fundamental tool to explore the physical/chemical evolution of the ISM content in SB and AGN. In the course of the combined IRAM 30m+PdBI survey we have studied a limited sample of SB and AGN. The first findings have revealed already clear study cases of large-scale shocks at work (NGC 253, M 82), propagation of PDR chemistry in SB (M 82) or XDR chemistry driven by AGN (NGC 1068).

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